The Heart of the Matter
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Design Review 1

1. Introduction

Cardiomyopathy, enlarged heart syndrome, causes the walls of the heart to thicken to an abnormal degree. While several types of cardiomyopathy are common among people, hypertrophic cardiomyopathy is one of the most common among young people, especially athletes, who suffer from unexpected cardiac arrest. As the walls of the heart thicken, blood is unable to pass through the ventricle. While symptoms of the disease do not exist for many carriers of cardiomyopathy, this obstruction often presents itself as heart arrhythmias. Young athletes who participate in rigorous physical activities are more likely to suffer from heart arrhythmias, and more severely, cardiac arrest, due to cardiomyopathy. Tests for cardiomyopathy are not integrated into standard physicals, so the disease is difficult to catch until severe problems arise. The purpose of our Senior Design project is to create a device which looks for signs of this disease.

2. The Problem

Physicians usually do not specifically test for cardiomyopathy due to the rarity of the disease and because ultrasounds and x-rays, the only completely accurate tests to determine enlarged hearts, are expensive. Our senior design project aims at looking for symptoms of the disease, specifically abnormal pulses (arrhythmia) and blood oxygenation levels. People with cardiomyopathy often have pulses with a “twice beating” rhythm, which are occasionally difficult to detect with a standard touch or stethoscope testing. Oxygen level testing is absent entirely from most standard check-ups. However, abnormalities in both pulses and oxygen levels may point to larger problems in the heart. The device we create will be able to show abnormalities that would prompt the patient to get further testing.

3. The Solution

We are creating a photoplethysmography (PPG) instrument to observe blood oxygenation levels and heartbeat regularity. Photoplethysmography is an optical method of measuring an organ’s volume by way of infrared and red light. The change in volume caused by the pressure pulse is measured according to the amount of light transmitted to a photodiode.

We have developed an optical sensor utilizing the principles of photoplethysmography. The transmitter of our device consists of two LEDs, one red (660 nm) and one infrared (940 nm), which are connected antiparallel to each other, and driven by a timer module contained within the TI AFE4490, an integrated analog front-end for pulse oximetry applications. As each LED flashes, the skin is illuminated by light at that particular wavelength. Photons, either reflected or transmitted through the skin, strike the receiver to generate an analog current, which is measured by the AFE. This analog current is converted to a 22-bit digital value representing the voltage of the signal. This digital value is sent back to the microcontroller by SPI communication on the SOMI connection. Within the microcontroller, these values are converted to actual voltages, and then sent on to the SD card for storage--again via SPI.

On the software level, the microcontroller is programed as the master with the AFE as the slave in the SPI communication system. By implementing successive SPI write commands, a timer module is programmed on the AFE by setting values for particular registers, which govern the duration of functional time blocks. It is during these time blocks that the LEDs are flashed at a specified frequency, the light incident upon the receiver is sampled, and the analog current values from the receiver are converted to corresponding digital voltages. Once these timers are set by write instructions from the microcontroller to the AFE, a read command is sent and the cycle of flashing, sampling, and converting repeats for continues to repeat, sending the voltage values back to the microcontroller, which are ultimately sent to the SD card as noted above.

4. Overall System Block Diagram

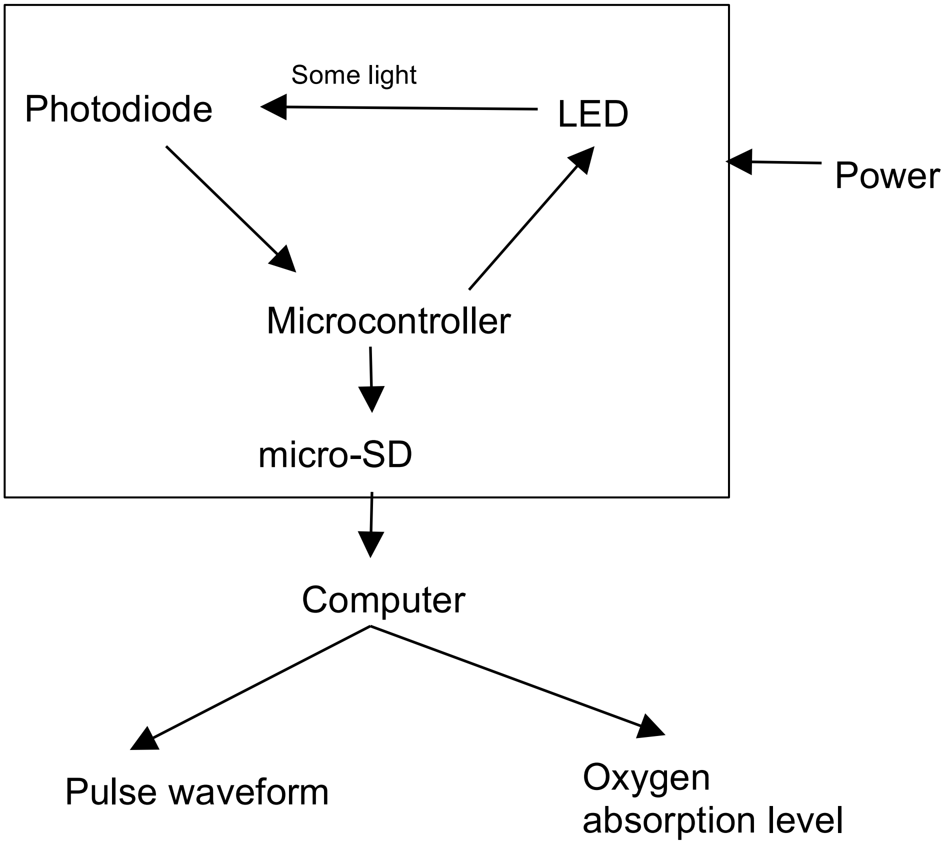


Figure 1. System Block diagram

5. Subsystem Block Diagram

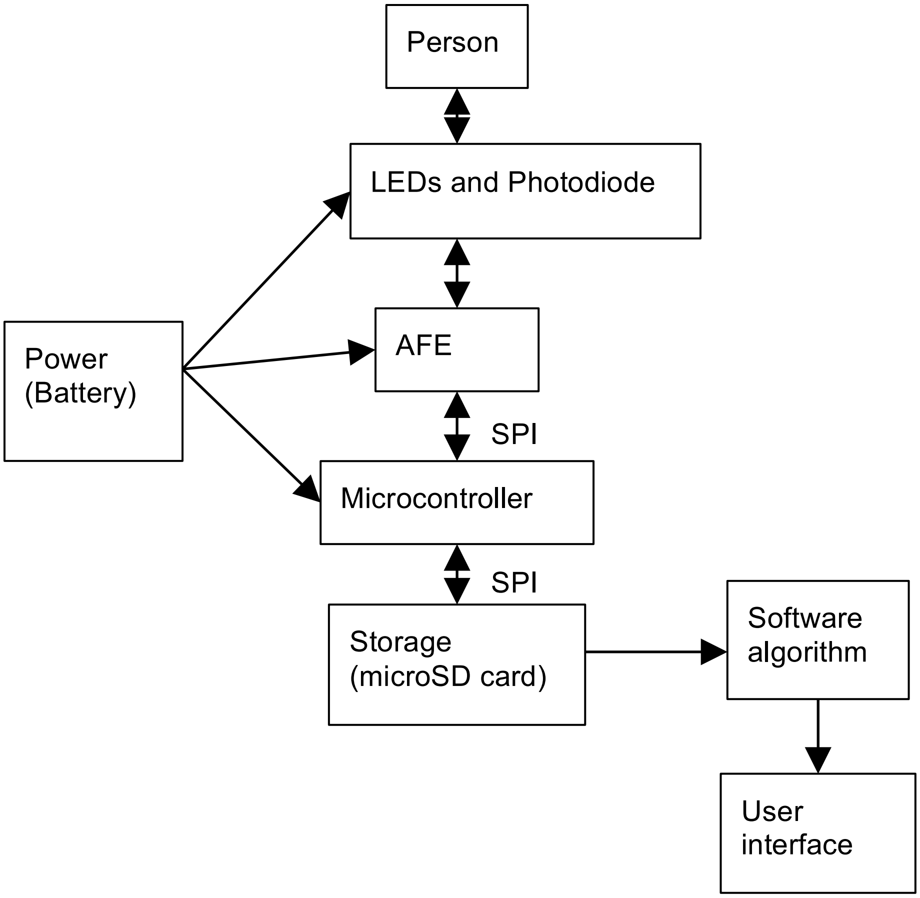


Figure 2. Subsystem Block Diagram

6. Subsystems

6.1 LEDs and Photodiode Hardware

Using the evaluation board for testing, a hardware system with the dual red/IR LED and photodiode provided accurate data of the pulse waveform. The dual red/IR LED and photodiode are antiparallel. For the initial design review, we soldered small wires to the dual red/IR LED surface mount part, part number VSMD66694. The anode of the IR LED (cathode of the red LED) and cathode of the IR LED (anode of the red LED) were wired with two wires to a DB9 connector, which fed into the evaluation board. On a separate board, the photodiode, coupled with a 5 uF capacitor, was also connected to the DB9, which fed into the evaluation board. The following diagrams from the AFE4490 datasheet show the dual LED and photodiode systems:

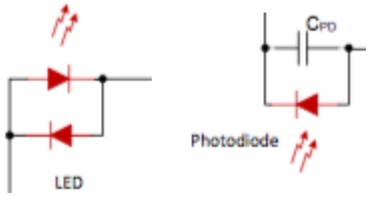


Figure 3. Sensor System

Starting the Texas Instruments simulation, which models the AFE4490 evaluation board output on the computer, a finger was placed in between the dual LED and photodiode. The AFE4490 controls the flashing rate of the LEDs. Light shined through the finger, and the finger absorbed some of the red and IR light. Using transmittance, the photodiode, on the opposite side of the finger, captured the signal and sent it back through the AFE4490 and to the computer, outputting a pulse waveform. With testing, setting the current at 10 mA provides a clear pulse signal. Driving the current too high leads to saturation, and readable pulse waveforms fail to output on the computer.

6.2 MATLAB Data Processing

The recorded data is exported to an Excel document which is then read into MATLAB for data processing. An example of the raw data produced by the system, in terms of voltages across the photodiode, can be seen below.

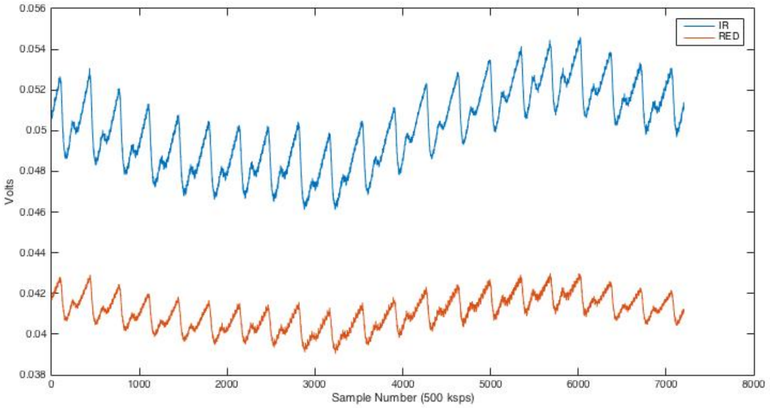


Figure 4. Pulse waveforms generated from photodiode and LEDs

The first step in processing this data is to change these voltages to relative concentrations of deoxygenated and oxygenated hemoglobin utilizing equations 1 and 2. They take into consideration the molar extinction coefficient of blood at both wavelengths to determine how a change in light attenuation is related to change in concentration of HbO2 and Hb. This generates waveforms that more closely resemble the expected Blood Pulse Volume (BPV) waveform.

Equations 1 and 2[2]

$$\Delta c_{\mathrm{HbO_2}} = \frac{\alpha_{\mathrm{Hb}}^{\lambda_1} \frac{\Delta A^{\lambda_2}}{L^{\lambda_2}} - \alpha_{\mathrm{Hb}}^{\lambda_2} \frac{\Delta A^{\lambda_1}}{L^{\lambda_1}}}{\alpha_{\mathrm{Hb}}^{\lambda_1}\alpha_{\mathrm{HbO_2}}^{\lambda_2} - \alpha_{\mathrm{Hb}}^{\lambda_2}\alpha_{\mathrm{HbO_2}}^{\lambda_1}},$$

$$\Delta c_{\mathrm{Hb}} = \frac{\alpha_{\mathrm{HbO_2}}^{\lambda_1} \frac{\Delta A^{\lambda_2}}{L^{\lambda_2}} - \alpha_{\mathrm{HbO_2}}^{\lambda_2} \frac{\Delta A^{\lambda_1}}{L^{\lambda_1}}}{\alpha_{\mathrm{HbO_2}}^{\lambda_1}\alpha_{\mathrm{Hb}}^{\lambda_2} - \alpha_{\mathrm{HbO_2}}^{\lambda_2}\alpha_{\mathrm{Hb}}^{\lambda_1}}.$$

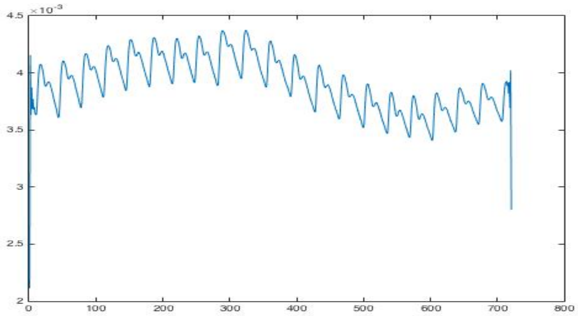


Figure 5. HbO2 concentration waveform resampled

The next step is to separate each pulse using the findpeaks function and to solve for parameters such as the pulse wave duration, pulse wave amplitude, pulse propagation time, and the time differences between the systolic and diastolic phases. These parameters are averaged over a given time period to create an "average pulse" from which indicators of cardiac health are examined.

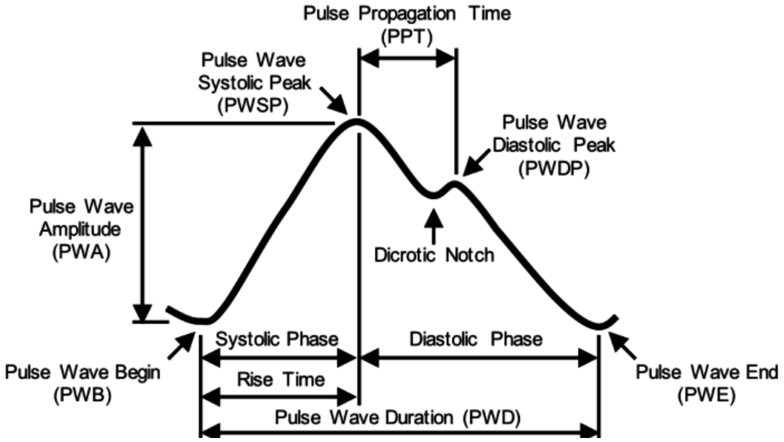


Figure 6. Blood Volume Pulse (BVP) waveform and parameters[1]

After heart rate, one of the first indicators to look at is the heart rate variability (HRV). This is the standard deviation of the Pulse Wave Duration of 5 minutes to 24 hours worth of pulse data. It measures how well the heart responds to the autonomic nervous system. High values indicate a healthy response. Another indicator of heart health is the Augmentation Index which is a ratio of the PWSP and PWDP as labeled on Figure 3. This indicates arterial stiffness. Finally, the inflection point area ratio is calculated. This is the ratio of the integral of the signal before the dicrotic notch divided by the integral of the signal after the dicrotic notch. It is an indicator of total peripheral resistance.[3]

6.3 Microcontroller communication with the AFE4490

The digital subsystems of our project communicate via serial peripheral interface bus (SPI). The microcontroller and the AFE exchange data over master-out-serial-in (MOSI) and master-in-serial-out (MISO) connections with the PIC as the master and the AFE as the slave. There is an 8 MHz ceramic oscillator attached to the AFE which drops the clock rate to its operating frequency of 4MHz. This clock signal is then routed back to the microcontroller so that the two components are running on a synchronized clock; this greatly reduces communication errors often caused by misaligned clock signals. An initial series of write instructions sets up the extensive timing module on the AFE which controls the LED flashing, photodiode sampling sequence, and A/D conversion, as detailed below. Also in this series of write instructions are the specifications for the gain stages, control registers (delineating various operational modes and reference voltages), and the current values for the LEDs to manipulate brightness.

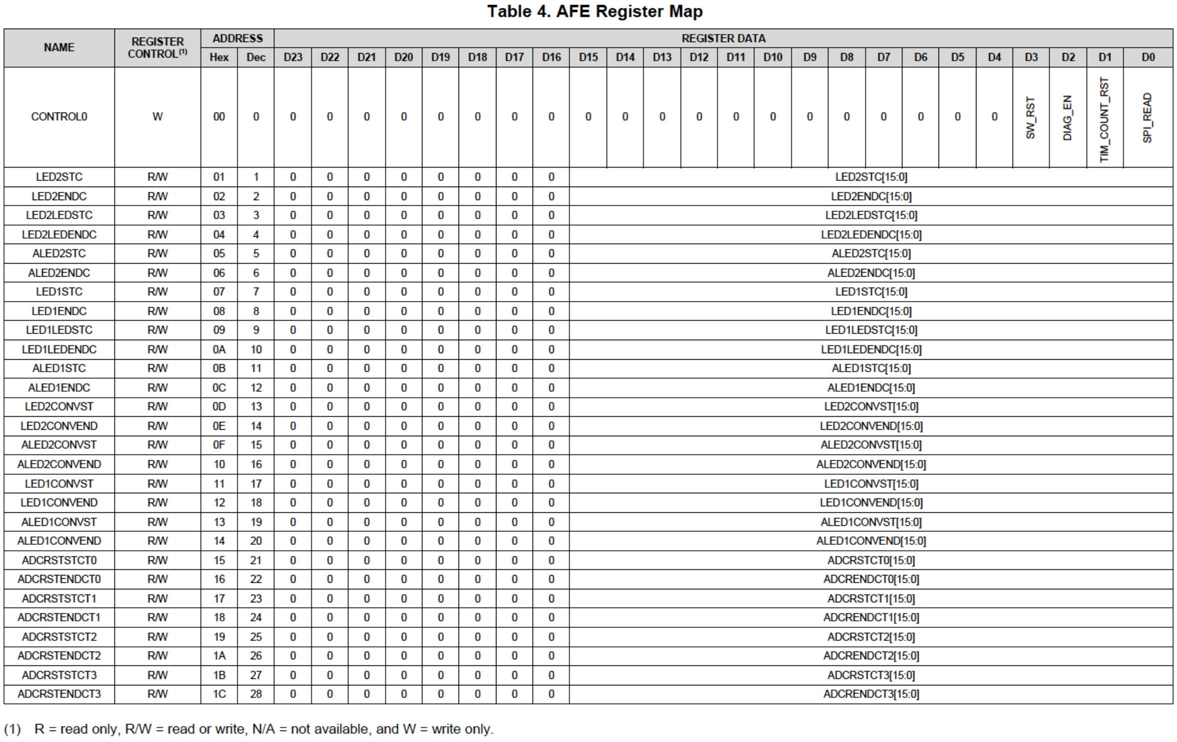
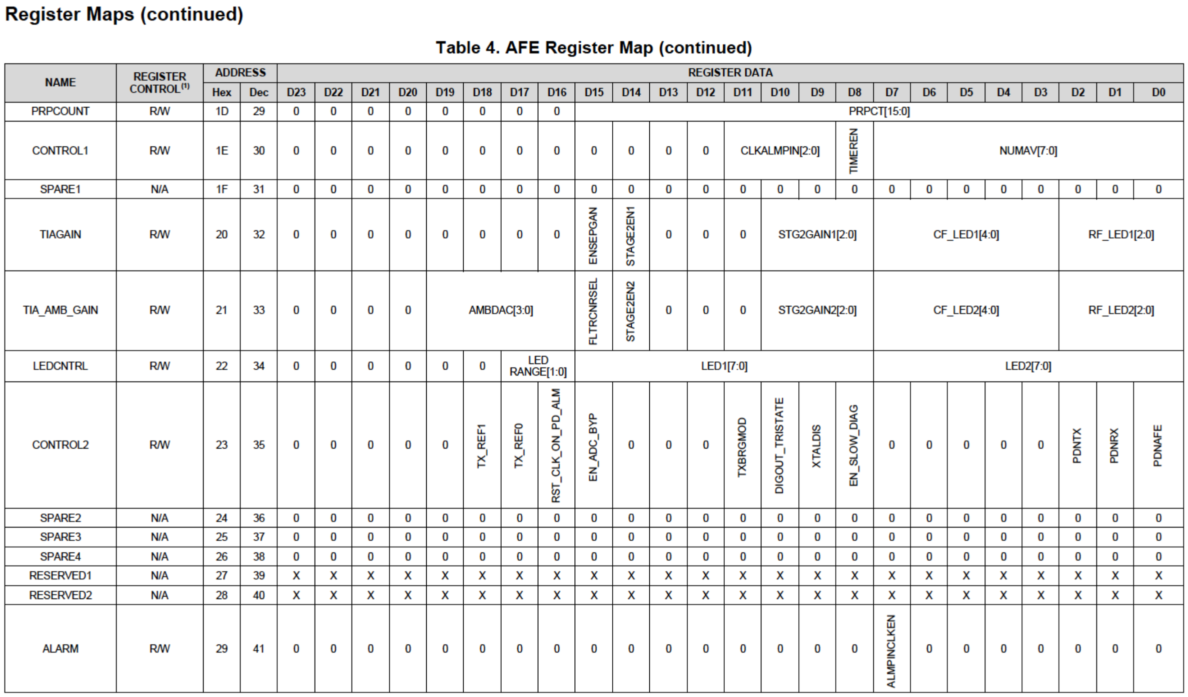


Table 4. AFE Register Map

NAME	REGISTER CONTROL[1]	ADDRESS		REGISTER DATA																							
		Hex	Dec	D23	D22	D21	D20	D19	D18	D17	D16	D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
CONTROL0	W	00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	SW_RST	DIAG_EN	TIM_COUNT_RST	SPI_READ
LED2STC	R/W	01	1	0	0	0	0	0	0	0	0	LED2STC[15:0]															
LED2ENDC	R/W	02	2	0	0	0	0	0	0	0	0	LED2ENDC[15:0]															
LED2LEDSTC	R/W	03	3	0	0	0	0	0	0	0	0	LED2LEDSTC[15:0]															
LED2LEDENDC	R/W	04	4	0	0	0	0	0	0	0	0	LED2LEDENDC[15:0]															
ALED2STC	R/W	05	5	0	0	0	0	0	0	0	0	ALED2STC[15:0]															
ALED2ENDC	R/W	06	6	0	0	0	0	0	0	0	0	ALED2ENDC[15:0]															
LED1STC	R/W	07	7	0	0	0	0	0	0	0	0	LED1STC[15:0]															
LED1ENDC	R/W	08	8	0	0	0	0	0	0	0	0	LED1ENDC[15:0]															
LED1LEDSTC	R/W	09	9	0	0	0	0	0	0	0	0	LED1LEDSTC[15:0]															
LED1LEDENDC	R/W	0A	10	0	0	0	0	0	0	0	0	LED1LEDENDC[15:0]															
ALED1STC	R/W	0B	11	0	0	0	0	0	0	0	0	ALED1STC[15:0]															
ALED1ENDC	R/W	0C	12	0	0	0	0	0	0	0	0	ALED1ENDC[15:0]															
LED2CONVST	R/W	0D	13	0	0	0	0	0	0	0	0	LED2CONVST[15:0]															
LED2CONVEND	R/W	0E	14	0	0	0	0	0	0	0	0	LED2CONVEND[15:0]															
ALED2CONVST	R/W	0F	15	0	0	0	0	0	0	0	0	ALED2CONVST[15:0]															
ALED2CONVEND	R/W	10	16	0	0	0	0	0	0	0	0	ALED2CONVEND[15:0]															
LED1CONVST	R/W	11	17	0	0	0	0	0	0	0	0	LED1CONVST[15:0]															
LED1CONVEND	R/W	12	18	0	0	0	0	0	0	0	0	LED1CONVEND[15:0]															
ALED1CONVST	R/W	13	19	0	0	0	0	0	0	0	0	ALED1CONVST[15:0]															
ALED1CONVEND	R/W	14	20	0	0	0	0	0	0	0	0	ALED1CONVEND[15:0]															
ADCRSTSTCT0	R/W	15	21	0	0	0	0	0	0	0	0	ADCRSTCT0[15:0]															
ADCRSTENDCT0	R/W	16	22	0	0	0	0	0	0	0	0	ADCRENDCT0[15:0]															
ADCRSTSTCT1	R/W	17	23	0	0	0	0	0	0	0	0	ADCRSTCT1[15:0]															
ADCRSTENDCT1	R/W	18	24	0	0	0	0	0	0	0	0	ADCRENDCT1[15:0]															
ADCRSTSTCT2	R/W	19	25	0	0	0	0	0	0	0	0	ADCRSTCT2[15:0]															
ADCRSTENDCT2	R/W	1A	26	0	0	0	0	0	0	0	0	ADCRENDCT2[15:0]															
ADCRSTSTCT3	R/W	1B	27	0	0	0	0	0	0	0	0	ADCRSTCT3[15:0]															
ADCRSTENDCT3	R/W	1C	28	0	0	0	0	0	0	0	0	ADCRENDCT3[15:0]															

(1) R = read only, R/W = read or write, N/A = not available, and W = write only.



Register Maps (continued)

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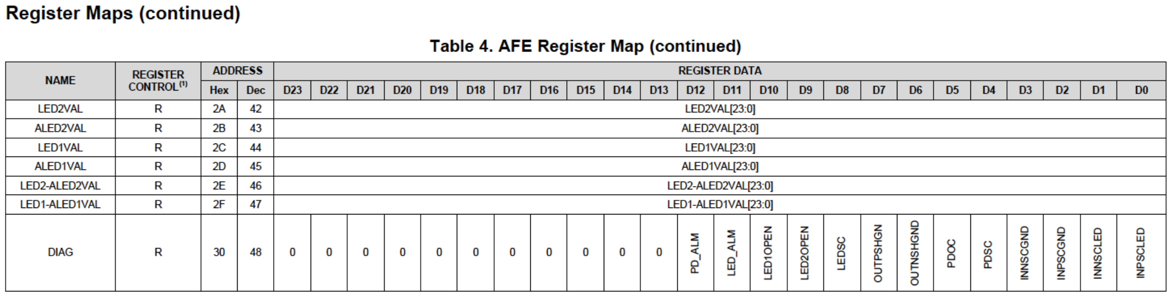
PRPCOUNT	R/W	1D	29	0	0	0	0	0	0	0	0	PRPCT[15:0]															
CONTROL1	R/W	1E	30	0	0	0	0	0	0	0	0	0	0	0	0	CLKALMPIN[2:0]			TIMEREN	NUMAV[7:0]							
SPARE1	N/A	1F	31	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TIAGAIN	R/W	20	32	0	0	0	0	0	0	0	0	ENSEPGAN	STAGE2EN1	0	0	0	STG2GAIN1[2:0]			CF_LED1[4:0]					RF_LED1[2:0]		
TIA_AMB_GAIN	R/W	21	33	0	0	0	0	AMBDAC[3:0]				FLTRCNRSEL	STAGE2EN2	0	0	0	STG2GAIN2[2:0]			CF_LED2[4:0]					RF_LED2[2:0]		
LEDCNTRL	R/W	22	34	0	0	0	0	0	0	LED RANGE[1:0]		LED1[7:0]								LED2[7:0]							
CONTROL2	R/W	23	35	0	0	0	0	0	TX_REF1	TX_REF0	RST_CLK_ON_PD_ALM	EN_ADC_BYP	0	0	0	TXBRGMOD	DIGOUT_TRISTATE	XTALDIS	EN_SLOW_DIAG	0	0	0	0	0	PDNTX	PDNRX	PDNAFE
SPARE2	N/A	24	36	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPARE3	N/A	25	37	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SPARE4	N/A	26	38	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RESERVED1	N/A	27	39	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RESERVED2	N/A	28	40	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ALARM	R/W	29	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	ALMPINCLKEN	0	0	0	0	0	0	0



Register Maps (continued)

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LED2VAL	R	2A	42	LED2VAL[23:0]																							
ALED2VAL	R	2B	43	ALED2VAL[23:0]																							
LED1VAL	R	2C	44	LED1VAL[23:0]																							
ALED1VAL	R	2D	45	ALED1VAL[23:0]																							
LED2-ALED2VAL	R	2E	46	LED2-ALED2VAL[23:0]																							
LED1-ALED1VAL	R	2F	47	LED1-ALED1VAL[23:0]																							
DIAG	R	30	48	0	0	0	0	0	0	0	0	0	0	0	PD_ALM	LED_ALM	LED1OPEN	LED2OPEN	LEDSC	OUTPSHGN	OUTNSHGND	PDOC	PDSC	INNSCGND	INPSCGND	INNSCLED	INPSCLED

Figure 7. AFE Register Map

After all these registers are initialized, the Control 0 register is switched to put the AFE into a continuous read mode during which it puts out data to the microcontroller. The digital values are sent back in 2's complement format in order to simplify the presentation of negative values. One of the software functions deployed to the microcontroller will convert this value to a functional voltage value falling within the range of acceptable values (+/- 1.2V) as noted by the microcontroller data sheet.

6.4 MicroSD card communication and Data Storage

When the microcontroller receives data back from the AFE, it sends the information to the MicroSD card so it can later be used to analyze on the computer. In order for us to use the data, the SD card needs to have a file system so that the information can then be read from a file. The MicroSD card has a FAT32 (file allocation table) file system on it. In order to access the file system and open a file on there, we need to program the microcontroller to do so. There are two options for doing this, one is Microchip's Memory Disk Drive file system interface library which is supposed to work with the PIC32 and the other is FatFs which is a generic file system interface library which is supposed to be adaptable to work on many platforms. These both involve using SPI protocol to communicate with the SD card. This will allow to write to the MicroSD card and create a file that can be read and used for our purposes on the computer.

6.5 Board Testing

Several "breakout" boards will be used for testing. The first breakout board includes the AFE4490, which will be connected to the microcontroller board used in class. This will allow us to test the microcontroller SPI communication with the AFE4490. The second breakout board includes the dual red/IR LED with pins on the end of the board to connect to the evaluation board. The final breakout board includes the photodiode coupled with a 5 uF capacitor, for noise cancelling purposes, with pins on the side of the board to connect the terminals to the evaluation board. Having these components soldered on small boards will allow us to more accurately test reflectance versus transmittance signals using the Texas Instruments AFE4490 evaluation board.

7. Final Overall Design Goals

The final design aims at connecting the subsystems mentioned above. The final board will include the PIC32MX270F256D microcontroller, pickit for microcontroller programming, AFE4490, battery and battery charging systems, and the microSD card system. The dual LED system and photodiode system will be on two separate boards if transmittance provides the best signal, or combined onto one board if reflectance provides the best signal. The main board will be on a belt that the user will wear and will connect to the LED/photodiode board(s) by wires. Using the microcontroller and AFE4490 to control the LED/photodiode system, the signals from the transmitted/reflected light will provide data to the microSD card. The user will be able to eject the microSD card from the main board and place it in a computer. Finally, the computer, with MatLab software, will output and analyze the waveforms from the data in the microSD card.